Precision Machine Design-Actuator2

2. Electromagnetic actuators for small range of motion

Solenoid actuator

A solenoid actuator is to generate a magnetic field that attracts the iron component to move toward the coil. The generated force is approximately given by

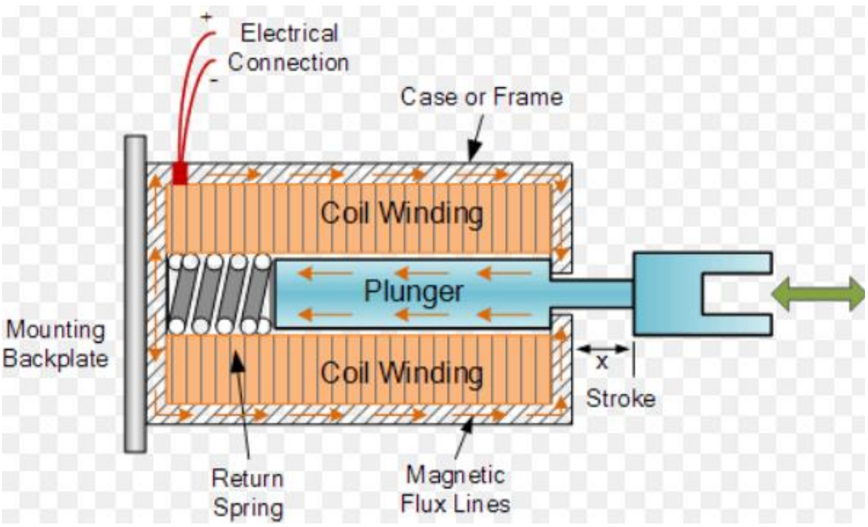
$F=\mu N^2 I^2 A/[2h^2]$ in [N]

Where μ is the magnetic permeability of air=$4\pi X 10^{-7}$[N/A^2]

N is number of turns

I is the current [A]

A is the pole area [m^2] and h is the air gap [m]

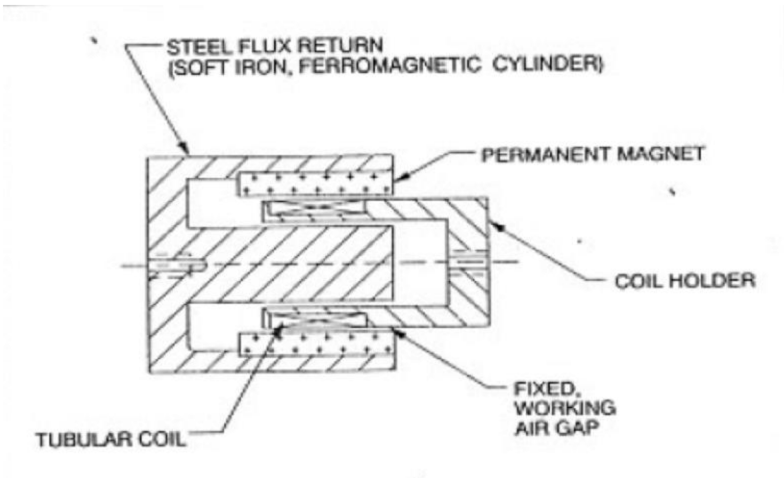


Solenoid actuator (source: https://www.electronics-tutorials.ws/io/io_6.html)

The length of iron path, magnetic property of material, area and shape of pole piece (plunger) are affecting parameters, and intrinsic nonlinear relationship between the force and current. The electro-mechanical constant is quite slow due to the magnetic field to be fully established fully only by the coil. It is often used as inexpensive actuators for moving components between fixed mechanical stops within the limited range of motion. Linear solenoids are useful in many applications that require an open or closed type motion such as electronically activated door locks, pneumatic or hydraulic control valves, robotics, automotive engine management, irrigation valves to water the garden, etc. and rotary version of solenoid actuators are also available.

Voice coil actuator

This actuator is the wound coil/permanent magnet actuator and it used in loud speaker. It is to use permanent magnet to get magnetic field, and small amount of input current to a coil inside the magnet structure generate in the magnetic field, thus moving the coil according to the Lorentz equation **F**=I**L**X**B,** where **F** is the generated force, I is the current flowing, **L** is the vector of wire whose magnitude is the line length, direction is the current flowing direction, **B** is the magnetic field. The moving coil actuator has higher dynamic performance than the solenoid actuator because the moving mass of coil is very small, and the magnetic field is pre-established by the permanent magnet. For limited range of motion application, voice coil actuator has much superior performance such as zero mechanical hysteresis, zero force ripple, zero backlash. The major drawback is, however, to generate heat like electric motors. Nanometer resolution can be achieved over a few mm range. There are various applications: computer hard disc head positioner, high speed mirror position devices or galvanometer for optical scanning, precision positioning for mirrors and lenses for high power lasers, and high precision control of silicon wafers in lithography application. Rotary version is also available for variable application.



Voice coil actuator (source:sensorwiki.org)

Piezo-electric actuator

The piezo actuator is to use the properties of piezoelectric materials such as d, g, and k constants, etc.

The d constant

Piezoelectric strain constant, d_{ij}, gives the relationship between the strain and the electric field applied.

$\varepsilon_j = d_{ij} E_i$

where ε_j is mechanical strain in the j direction, E_i is the electric field [V/m] in i direction. For i and j, 1 for δx, 2 for δy, 3 for δz, 4 for θx, 5 for θy, 6 for θz, respectively.

The g constant

Piezoelectric stress constant, g_{ij}, gives the relationship between the electric field and the stress.

$E_i = g_{ij} \sigma_j$

where E_i is the electric field [V/m] in I direction, and σ_j is the stress [Pa] in j direction.

The constant d_{ij} and g_{ij} are linearly related as

$d_{ij} = K \varepsilon_0 g_{ij}$

where K is the relative dielectric constant and ε_0 is the dielectric constant of free space, and it is 8.85E-12 [F/m].

Piezo coupling constant k

Piezo coupling constant is a measure of change from electrical energy to mechanical energy or vice versa.

k1=electric energy generated/mechanical energy applied

k2=mechanical energy generated/electrical energy applied

The piezo sensor is to use k1 constant, and piezo actuator is to use the k2 constant, and they are generally the same, and 0.1-0.8 depending on material. As the energy is stored in the form of elasticity or capacity in the material, these k constants can be understood as the transmission ratio, not energy efficiency.

Dielectric constant, K

Dielectric constant is a measure of amount of charge that the material can store when the material is positioned between two electrodes. Thus it is the same concept as the capacitance between the electrodes. Thus the piezoelectric material behaves like a capacitor, and it can be modeled as capacitor in the dynamic modeling of piezo actuator. The dielectric constant, K, can be defined as the ratio of capacitance at ambient to the capacitance at vacuum, and K>1 in case of dielectric material.

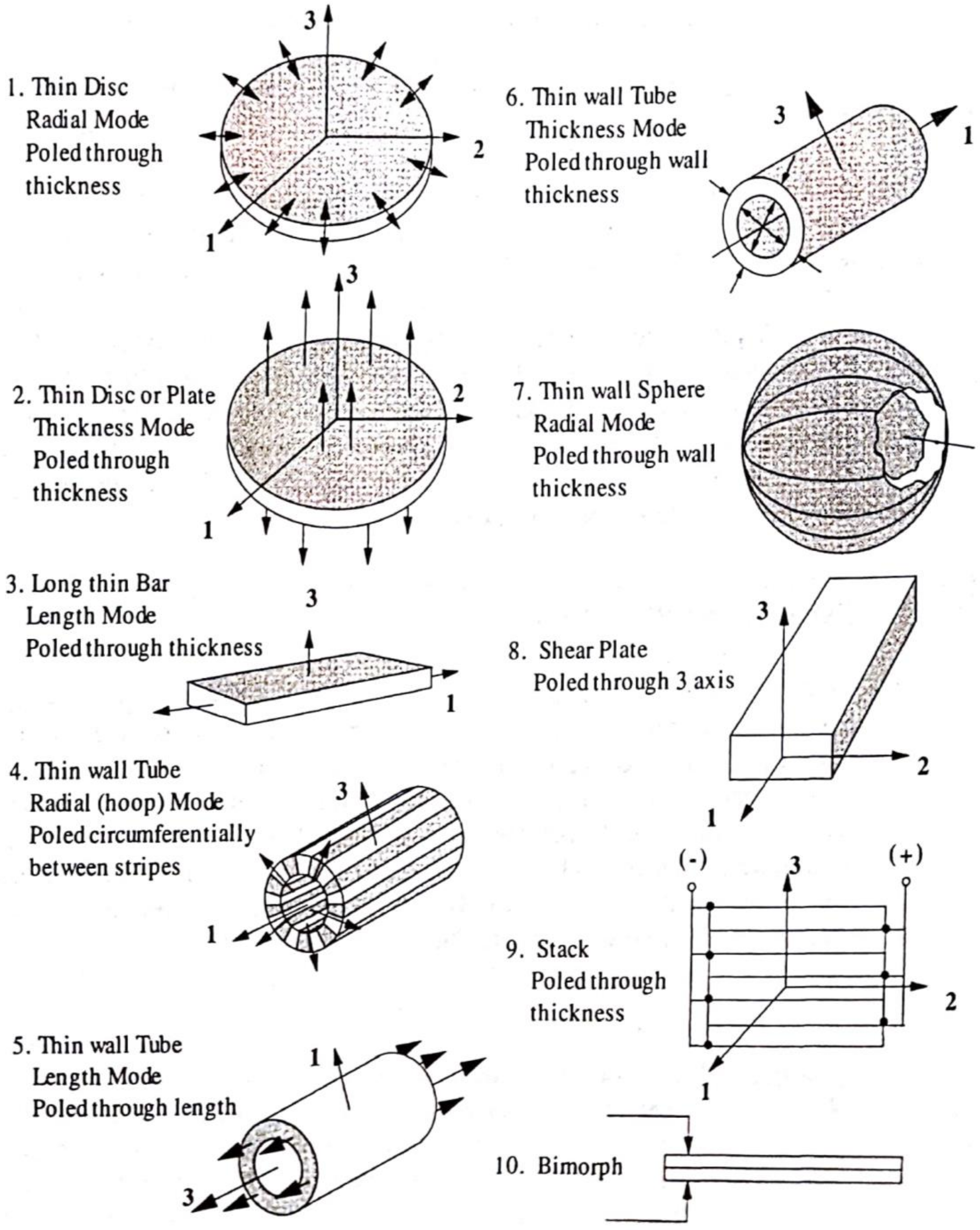
The following fig shows the typical properties for piezo electric materials.

	T limit (^oC)	Field dir.	Force dir.	d $x10^{-12}$	g	E (GPa)	K	k	Density ($10^3 kg/m^3$)	Wave vel. (m/s)
Quartz	550	X	X	2.3	0.0578	80	4.5	0.1	2.65	5400
		X	Y	2.3	0.0578	80	4.5	0.1		5400
Ammonium dihydrogen phosphate	120	Z	45^o XY	24	0.1750	19	15.5	0.29	1.8	3250
Rochelle salt	45	X	45^o YZ	290	0.0936	18	350	0.68	1.77	3200
		Y	45^o ZX	27	0.3316	10	9.2	0.3		2400
Barium titanate ceramic	45	Z	Z	190	0.0126	106	1700	0.52	5.7	4300
		Z	X	78	0.0052	110	1700	0.22		4400
Lead titanate zirconate (45/55)	100	Z	Z	140	0.0352	71	450	0.6	7.6	3100
		Z	X	57	0.0143	87	450	0.26		3400
Lead strontium titanate zirconate	300	Z	Z	250	0.0235	67	1200	0.64	7.5	3000
		Z	X	105	0.0099	81	1200	0.3		3300
Lead metaniobate	300	Z	Z	80	0.0402	60	225	0.42	6	3200
	300	Z	X	11	0.0055	60	225	0.04		3200

Typical properties of piezoelectric materials

(source: Slocum's precision machine design, after Jaffe)

Piezoelectric materials can be manufactured in a variety of shapes, and various available shapes are shown in the fig. Disc shape is one of most common type, where the polarization axis parallel to the length direction, and electrodes are placed at the end of disc, the disc type can be staked together to give cylinder type. The disc type can be changed not only in thickness direction, but also in planar or radial direction.

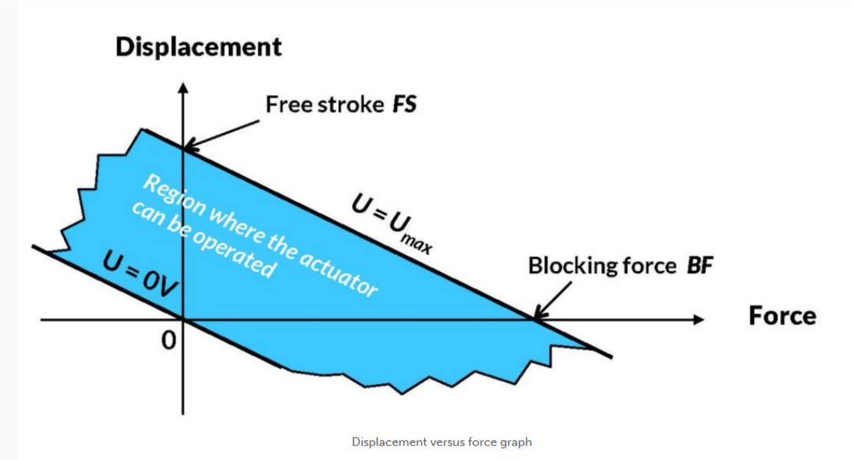


Various piezoelectric actuators

(source:Slocum's precision machine design)

For example, the piezoelectric material of lead titanate zirconate gives (sometimes called as PZT) d_{11} of 140E-12 [strain/V/m], thus it can give the change of 1.4 angtrom for the 1mm stack in the thickness direction when 1V is applied across the stack.

A piezoelectric actuator is usually manufactured by stacking or epoxying together a stack of piezoelectric materials and electrodes. The stack is then attached to a metal case that has bolt holes in it, so that the actuator can be bolted. Because the piezo stacks can have several modes of operation according to the d_{ij} constant, it is important not to over-constrain the stack itself, as it may result in non-accurate motion contrary to the design intention. Non-proper assembly of stacking may lead a shortening of life time of the piezoelectric actuators due to the fatigue failure, or sometimes crack failure may occur under wrong pressing in the transverse direction. For the actuator design, the stiffness and the range of stroke and force are primary factors; the follwing figure shows them for typical piezoelectric actuator application, where the range of stroke and force and the stroke are shown as the shaded area under applicable voltage range, giving the stiffness as the slope between the stroke and force. When K is the stiffness, m is the mass to be actuated, thus the natural frequency ω_n , period, T_0, can be obtained. The minimum servo control time is better to be faster than at least 3 times of the period of the piezo actuator, to avoid the aliasing. Thus the minimum servo control time = $T_0/3 = 2\pi[m/k]^{1/2}/3$ sec.

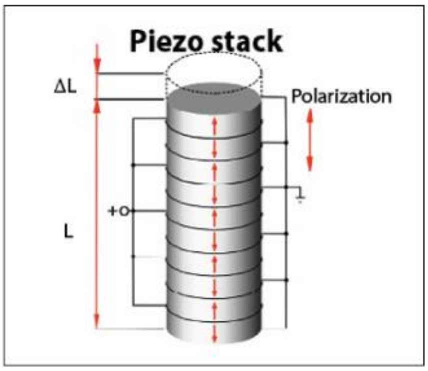


Free Stroke and Blocking Force

Typical range of stroke and force for piezoelectric actuators

(source:https://www.ctscorp.com/resource-center/tutorials/quasi-static-actuators/)

The piezoelectric actuator, usually, gives few KHz bandwidth depending on its mass and stiffness, and the resolution of angstrom can be achieved. Thus the piezo electric actuators can provide better performance of orders of magnitude when compared to other similar actuators. Also, the piezoelectric actuator dissipates only few mW power, thus does not give any serious thermal problems, while equivalent electro-magnetic actuators usually generate heats with order of magnitude higher, due to winding resistance and eddy current losses. There are wide applications for the piezoelectric actuator: scanners for scanning interferometry such as white light interferometry or phase shift interferometry, scanners for AFM and STM, micro positioning stage for various ultra-precision application, micro actuators for precision movement or gripping operation, etc.



(source: PI company) (source: Motion system design, www.micromo.com)